Thermosphere-Ionosphere-Mesosphere Modeling Using the TIE-GCM, TIME-GCM, and WACCM that will lead to the Development of a Seamless Model of the Whole Atmosphere

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LONG-TERM GOALS

A major goal of this research is to understand how elements in the coupled upper atmosphere/ ionosphere system interact with one another and to determine how this coupled system responds to the variable energy input from the sun and the variable input from the lower atmosphere and ocean. The research focuses on understanding the sources and characteristics of global-scale ionospheric, thermospheric, and mesospheric structure and variability and the coupling of those atmospheric regions to the lower atmosphere and ocean and to the magnetosphere and solar wind. The long-term goal is to use this research to help in the development of a seamless model of the atmosphere that extends from the ground and ocean to the exosphere of the atmosphere near 500−700 km altitude. The information from this research will be useful for ONR to develop a seamless operational model that simulates the present day structure and dynamics of the thermosphere-ionosphere-mesosphere-lower atmosphere-system including its response to solar variability and global change.

OBJECTIVES

Our scientific objectives are to understand the nature of the sources of variability in the upper atmosphere/ionosphere system and how they are related to solar radiative and auroral particle and electric field forcings. We are also interested in understanding how disturbances from the lower atmosphere and ocean affect the upper atmosphere and how this variability interacts with the variability generated by solar and auroral sources. We accomplish this task by developing large-scale numerical models of the upper atmosphere and ionosphere and using these models to analyze data obtained by satellites and ground-based observatories as well as using these models for numerical simulations to understand how upper atmosphere/ionosphere physics and chemistry interact. We are also developing a model of the whole atmosphere extending between the ground and 500 km for use in simulating and analyzing atmospheric variability and for studying solar and auroral influences on the entire atmosphere. This model, once fully developed and verified, will be useful for predictions of atmospheric circulation, temperature and compositional structure, space weather and global change.

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APPROACH

A hierarchy of numerical models has been developed that describes the upper atmosphere and ionosphere and these models have been constantly improved and used to study atmosphere/ionosphere interactions and their response to solar and auroral variability for over 25 years. The current version of models include: the TIE-GCM and TIME-GCM, where T, I, M, and E represent “thermosphere,” “ionosphere,” “mesosphere,” and “electrodynamics,” respectively, and GCM represents “general circulation model.” Both models include self-consistent ionospheric electrodynamics, that is, a calculation of the electric fields and currents generated by the ionospheric dynamo, and consideration of their effects on the neutral dynamics. The TIE-GCM is used for studies that focus on the thermosphere and its coupling with the ionosphere and magnetosphere. The TIME-GCM, the most elaborate of the upper-atmospheric TGCMs, solves for global distributions of neutral and plasma temperatures, velocities, and compositions, including all of the species that are photochemically important in the upper stratosphere, mesosphere, thermosphere, and ionosphere. The Whole Atmosphere Community Climate Model (WACCM) is a model that currently extends between the ground and ocean and 150 km altitude. WACCM is a seamless model of the entire atmosphere that includes couplings between dynamics and chemistry that will eventually absorb all of the capabilities of the other upper atmosphere TGCMs and extend to about 700 km altitude.

In addition to the above models we also use the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) model to provide auroral inputs and a Global Scale Wave Model (GSWM) to study tides and planetary wave propagation in the atmosphere. The latter is a linearized model that is useful in helping understand tidal and wave phenomena in the non-linear TGCMs. We also have a small-scale gravity wave model to examine processes and develop parameterizations of these processes for inclusion in the global models. We also have a model of solar EUV and UV irradiance variations based on satellite data, an empirical model of thermospheric nitric oxide, and new and improved ion convection models for the high latitude thermosphere. We also have a global mean model that is useful for testing the impact of new parameterizations and ideas of upper atmosphere processes before including them in the TGCMs and WACCM.

NCAR personnel participating in this work include: Raymond Roble (aeronomy and global upper atmosphere and ionospheric dynamics), Arthur Richmond (electrodynamics and upper atmosphere waves), Hanli Liu (gravity wave parameterizations), Maura Hagan (tides and planetary waves), Barbara Emery and Gang Lu (campaign studies and data analysis), and Benjamin Foster (programming support and model development). The Whole Atmosphere Community Climate Model (WACCM) is a collaborative effort between three NCAR Divisions: The High Altitude Observatory (HAO), The Climate and Global Dynamics Division (CGD), and the Atmospheric Chemistry Division (ACD). This is a collaborative effort involving at least 20 NCAR scientists and numerous outside collaborators.

WORK COMPLETED

Completion of Global Mean Model Rewrite: Finished a complete rewrite of the global mean 1-d column model (glbmean). The new source code and supporting run and configuration scripts were completed in mid-April. Work has continued in 2005−2006 tuning the model, and incorporating the scripts and source code into the overall TGCM model structure at HAO and SCD. This new version of the code has been given to David Siskind (NRL) for use in studying the physical and chemical processes controlling the O/O2 ratio in the lower thermosphere in an effort to simulate satellite data.

TIEGCM: Worked towards release of version 1.8 (formal release was in January 2006) and eventual release of v2.0. Components and features of this and subsequent releases were designed by the "TGCM Development Group." Two major improvements to the model include extension of the lower boundary to 80 km, and a new history file format that will conform to netCDF Climate and Forecasting (CF) conventions. This model is being developed at double vertical resolution with 4 grid points per scale height and a latitude/longitude grid of 2.5 degrees. The higher resolution model is needed to resolve the diurnal and semi-diurnal tidal propagation in the lower thermosphere and for better electron density and electrical conductivity distributions for the dynamo.

New History File Format: A new model history format has been developed to conform to the netCDF CF conventions (these are also used by CGD community climate models). The new format is designed with the following primary goals:

a) To more accurately represent TIEGCM and TIMEGCM model results (e.g., midpoints and interfaces in the vertical dimension, lower boundary data without post-processing, with the removal of some historical artifacts and conventions).

b) Use of metadata to more thoroughly and accurately explain the data on the history files (variable and global file attributes, units, coordinate arrays, data files used, etc.).

c) Enable the histories to "stand on their own," while still providing the option of using our post-processors for diagnostics and visualization.

d) To conform to netCDF CF conventions, enabling better use of publicly available netCDF browsers and visualization software.

e) New user interface to storing fields on secondary histories (geographic and magnetic coordinate variables, 3-d and 4-d variables, and metadata description) (module addfld replaces addfsech).

TIME-GCM:

a) Release of a new updated version - timegcm1.2.

b) Incorporation of solar proton event data, and medium electron and proton data (MEPED) from NOAA.

c) Improved radiative cooling parameterizations and diagnostics.

d) Greatly improved the flexibility of processing model output for comparison with ground-based and satellite data.

WACCM3: WACCM includes self-consistent interactions throughout the troposphere, stratosphere, mesosphere and lower thermosphere. The dynamical model has been extended to include molecular diffusion, a gravity wave spectrum parameterization, non-LTE radiation processes and a finite volume dynamical core. Much of the past year has been devoted to tuning the model by improving the gravity wave parameterization within the model and comparing model predictions of dynamics and chemical species such as ozone, water vapor, methane, nitrogen dioxide and other chemical species with data that are currently being measured by satellites. In addition, a realistic magnetic field model has been included in WACCM3 to better predict the location and motion of auroral processes at high magnetic latitudes and for a better prescription of ion drag throughout the ionosphere and thermosphere.

RESULTS

The results from some of the studies conducted during the past year include the following:

- Roble and Dickinson (1989) showed that global change is not confined only to the troposphere and stratosphere but that trace gases and changes in lower atmosphere structure could also have a corresponding influence on the upper atmosphere. They used the best available non-LTE CO2 radiation code and understanding of aeronomy based on the ground-based, laboratory and satellite data available at the time. However, considerable progress has been made in improving our understanding of many processes and Roble and Solomon (2005) found that a considerable update was needed for many processes, such as rate coefficients, NO densities and solar X-rays based on recent satellite observations. In implementing the new aeronomical updates it was found that the original estimates of thermospheric cooling were overestimated as well as in subsequent modeling studies that only consider CO2 cooling. The original calculations were based on lower NO number densities than are currently observed. Higher levels of solar soft X-rays and an improved photoelectron parameterization now produce significantly more NO in better agreement with observations. In the earlier studies, NO did not enter significantly into the energy budget of the thermosphere and nearly all of the cooling was due to CO2. Current work indicates that there is a significant change to the predicted global change response primarily based on increased cooling from the NO 5.3 micron band. NO is highly dependent on solar and geomagnetic activity, so NO radiation is much larger during maximum. NO cooling acts as a regulator, causing the predicted global change to become smaller at solar maximum than at solar minimum. The original predicted global exospheric temperature decrease of 100K is reduced to 30K for solar moderate conditions, slightly less for solar maximum and 40K for solar minimum. The corresponding density percent changes are considerably different from solar minimum to solar maximum, ~ 40% decreasing to ~ 20% depending upon altitude. These estimates, which translate into ~ -4%/decade and ~ -2%/decade for current rates of CO2 increase, are in reasonable agreement with estimates based on satellite orbit analysis.

The global mean model was used by Qian et al. (2006) to simulate the thermospheric density change at 400 km over a 30 year period from 1970 to 2000 using the measured CO2 increase over the same period. The results agreed well with satellite drag data obtained over the same period. In addition, the model was used to predict that the long-term change of thermospheric neutral density from 2006 to the end of solar cycle 24 will be about 2.7%/decade at 400 km.

- Liu and Roble used NCEP data and a NCAR TIME-GCM simulation to explore the dynamical coupling of the stratosphere and mesosphere during the 2002 Southern Hemispheric major stratospheric sudden warming. The analyses suggest the possibility of feedback interactions between the planetary wave forcing and the mesospheric/stratospheric mean state changes. Multiple strong planetary waves before the warming penetrate into the mesosphere and weaken the polar jet. They alter the wave transmission condition in favor of more upward-poleward propagation of the wave energy at progressively lower altitudes. The jet reversal and the planetary wave surf zone also descend from the mesosphere down to the stratosphere, making wave breaking more likely at decreasing altitudes with each wave episode. These changes in the wave transmission and breaking conditions in the mesosphere and stratosphere may be critical for the extensive major stratospheric warming.

Liu, H.-L. and R. G. Roble, Dynamical coupling of the stratosphere and mesosphere in the 2002 Southern Hemisphere major stratospheric sudden warming, *Geophys. Res. Lett., 32,* L13804, doi:10.1029/2005GL022939, 2005.

- The 5-day wave is the gravest symmetric Hough mode of westward propagating zonal wavenumber 1. This wave is observed using the SABER instrument aboard the TIMED satellite during the first three years of the spacecraft mission (2002−2004). Supporting measurements were made with mesospheric radar systems. To better interpret the observations, Riggin et al. employed the NCAR TIME-GCM simulation of year 2003 for comparative analysis. For the simulation the lower boundary was specified using NCEP data. The climatology from SABER shows a May maximum in the amplitude of the 5-day wave, which is consistent with the seasonal dependence found in earlier studies. A particularly strong wave with a ~6 day period was observed in May 2003 and is studied in some detail. There is considerable evidence from both data and model in this study that a major source for this wave was in the southern (winter) hemisphere. Cross-equatorial ducting allowed the wave to propagate into the northern (summer) hemisphere, where it was amplified by baroclinic instability.

Riggin, D. M., H.-L. Liu, R. S. Lieberman, R. G. Roble, J. M. Russell III, C. J. Mertens, M. G. Mlynczak, D. Pancheva, S. J. Franke, Y. Murayama, A. H. Manson, C. E. Meek, and R. A. Vincent, Observations of the 5-day wave in the mesosphere and lower thermosphere, *J. Atmos. Sol.-Terr. Phys.*, *68,* 323−339, doi:10.1016/j.jastp.2005.05.010, 2006.

- Oberheide, Liu, Gusev, and Offerman used carbon monoxide, temperature, and potential vorticity data (November 1994) from the CRyogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) experiment to analyze the relationship between the mesospheric surf zone in the winter hemisphere and simultaneously observed thermal inversions just above. The observed upward propagating planetary waves rapidly decay when they approach the critical wind line in the upper mesosphere and a distinct surf zone is formed between 60−75 km. Above 85 km, the planetary wave activity increases again revealing an out-of-phase behavior with the waves below. This is likely due to momentum forcing associated with breaking gravity waves that have been filtered by the stratospheric and lower mesospheric planetary waves. The abrupt vertical phase shift of the planetary waves thus induces a strong vertical geopotential curvature that is sufficiently large, through hydrostatic equilibrium, to invert the thermal structure around 80 km. The CRISTA observations and their interpretation are consistent with simulations of the TIME-GCM that were run for the same time period. Both the observation and the model results point to a more indirect, though essential, role of the gravity waves in the formation of the mesospheric inversion layers in early winter 1994.

Oberheide, J., H.-L. Liu, O. A. Gusev, and D. Offermann, Mesospheric surf zone and temperature inversion layers in early November 1994, *J. Atmos. Sol.-Terr. Phys.,* doi:10.1016/ j.jastp.2005.11.013, in press, 2006.

- Xu et al. used TIMED/SABER temperature observations and TIME-GCM simulations to study the global structure and variability of the mesopause altitude and temperature. There are two distinctly different mesopause altitude levels: the higher level at 95−100 km and the lower level below ~86 km. The mesopause of the middle and high latitude regions is at the lower altitude in the summer hemisphere for about 120 days around summer solstice, and is at the higher altitude during other seasons. But at the equator the mesopause altitude is at the higher altitude for all seasons. In addition to the seasonal variation in middle and high latitudes, the mesopause altitude and temperature undergo modulation by diurnal and semi-diurnal tides at all latitudes. The mesopause is about 1 km higher at most latitudes and 6−9 K warmer at middle to high latitudes around December solstice than around June solstice. These can also be interpreted as hemispheric asymmetry between mesopause altitude and temperature at solstice. They also studied the possible causes of the asymmetry as related to solar forcing and gravity wave forcing using TIME-GCM.

Xu, J., H.-L. Liu, W. Yuan, A. K. Smith, R. G. Roble, C. J. Mertens, J. M. Russell III, and M. G. Mlynczak, Mesopause structure from TIMED/SABER observations, *J. Geophys. Res. (Atmosphere)*, submitted, 2006.

- Matsuo et al. examined the ability of the Ensemble Kalman Filter (EnKF) to assimilate a realistic set of space-based observations currently available in the mesosphere and lower thermosphere (MLT) region. An EnKF assimilation system has been constructed using a time-dependent, dynamical, chemical stratosphere-mesosphere model with the NCAR Data Assimilation Research Testbed (DART). The model error growth in the MLT region and its interaction with the EnKF are crucial in controlling the quality of the assimilation. In its standard form, the model displayed too little error growth, partly due to the lack of variability in forcing at the models lower boundary. This led to insufficient variance in filter assimilation prior estimates. Although this issue can technically be rectified, physical reasons for the existence/lack of natural model error growth in current GCMs for the MLT region have not been conclusively understood. Sensitivity studies using the NCAR WACCM have revealed the presence of a surprisingly high degree of dynamical coupling between the troposphere and the MLT that may be playing a dominant role in controlling model error growth in the MLT region. The results shown here for the MLT region are valuable in order to improve future applications of data assimilation to this region and to other strongly forced models.

Matsuo, T., H.-L. Liu, J. L. Anderson, D. R. Marsh, and A. K. Smith, On model error growth in applications of an ensemble Kalman filter to the mesosphere and lower thermosphere region, *J. Geophys. Res.*, submitted, 2006.

Web site for the Thermospheric General Circulation models:
http://www.hao.ucar.edu/public/research/tiso/tgcm/tgcm.html

Web site for WACCM:
http://acd.ucar.edu/models/WACCM/

IMPACT/APPLICATIONS

The models we have developed are community models and they have been used by over 100 scientists and students over the past years. The models are constantly being evaluated, upgraded and improved by community feedback. We participate in NRL studies, NSF Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR), and Space Weather Initiative (SWI) programs. The models have been used for the Advanced Research and Global Observation Satellite (ARGOS) mission, the NASA Sun-Earth Connection Theory Program, the Atmosphere Explorer (AE), Dynamics Explorer (DE), Solar Mesosphere Explorer (SME), Upper Atmosphere Research Satellite (UARS), and the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) NASA missions as well as U.S. Air Force and Navy satellite missions. We have also participated in the CRISTA and the Middle Atmosphere High Resolution Spectrograph Investigation (MAHRSI) space shuttle experiments. We also participate in the NCAR Climate Systems Modeling effort in examining the couplings between the upper and lower atmospheres and in an attempt to understand the effects of the variable solar outputs on the coupled Earth system.

RELATED PROJECTS

The numerical modeling effort is complemented by a data analysis and interpretation effort. Data from the following satellites have been analyzed and compared with model simulations:

Navy ARGOS Satellite Mission
NASA Dynamics Explorer Mission
NASA Upper Atmosphere Research Satellite (UARS)
NASA CRISTA and MAHRSI Experiments Onboard the Space Shuttle
NASA Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) Satellite
NASA Solar Nitric Oxide Experiment (SNOE)
NASA Solar Radiation and Climate Experiment (SORCE)
NSF CEDAR Campaigns
NSF GEM Campaigns

REFERENCES

Roble, R. G. and R. E. Dickinson, How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere? *Geophys. Res. Lett., 16,* 1441−1444, 1989.

Roble, R. G. and S. C. Solomon, On modeling the upper atmosphere and ionosphere response to global change, invited paper presented at the spring AGU, New Orleans, LA, May 23−27, 2005.

PUBLICATIONS

Publications in FY2006

Liu, H.-L. and R. G. Roble, Dynamical coupling of the stratosphere and mesosphere in the 2002 Southern Hemisphere major stratospheric sudden warming, *Geophys. Res. Lett., 32,* L13804, doi:10.1029/2005GL022939, 2005 [published, refereed].

Oberheide, J., Q. Wu, T. L. Killeen, M. E. Hagan, and R .G. Roble, Diurnal nonmigrating tides from TIDI wind data: Monthly climatologies and seasonal variations, *J. Geophys. Res.,* doi:10.1029/2005JA011491, 2006 [published, refereed].

Oberheide, J., Q. Wu, T. L. Killeen, M. E. Hagan, and R. G. Roble, Diurnal nonmigrating tides from TIDI wind data: Monthly climatologies and seasonal variations−electronic supplement, *J. Geophys. Res.*, doi:10.1029/2005JA011491, 2006 [published, refereed].

Oberheide, J., Q. Wu, D. A. Ortland, T. L. Killeen, M. E. Hagan, R. G. Roble, R. J. Niciejewski, and W. R. Skinner, Nonmigrating diurnal tides as measured by the TIMED Doppler Interferometer:

Preliminary results, *Adv. Space Res., 35,* 1911−1917, doi:10.1016/ j.asr2005.01.063, 2005 [published, refereed].

Riggin, D. M., H.-L. Liu, R. S. Lieberman, R. G. Roble, J. M. Russell III, C. J. Mertens, M. G. Mlynczak, D. Pancheva, S. J. Franke, Y. Murayama, A. H. Manson, C. E. Meek, and R. A. Vincent, Observations of 5-day wave in the mesosphere and lower thermosphere, *J. Atmos. Sol.-Terr. Phys., 68,* 323−339, 2006 [published, refereed].

Oberheide, J., H.-L. Liu, O. A. Gusev, and D. Offermann, Mesospheric surf zone and temperature inversion layers in early November 1994, *J. Atmos. Sol.-Terr. Phys.,* doi:10.1016/ j.jastp.2005.11.013, 2006 [published, refereed].

Xu, J., H.-L. Liu, W. Yuan, A. K. Smith, R. G. Roble, C. J. Mertens, J. M. Russell III, and M. G. Mlynczak, Mesopause structure from TIMED/SABER observations and implications for gravity wave distributions, *J. Geophys. Res.,* 2006 [submitted].

Shepherd, G. G.,Y.-M. Cho, L. Guiping, M. G. Shepherd, and R. G. Roble, Correlations of airglow variabilites in the context of the global circulation, *J. Atmos. Sol.-Terr. Phys.*, 2006 [in press].

Tao, Y., C. Y. She, M. E. Hagan, T. Li, K. Arnold, T. D. Kawahara, B. P. Williams, P. E. Acott, J. D. Vance, D. Krueger, and R. G. Roble, Seasonal variations of diurnal tidal-period perturbations in the mesopause region temperature, zonal and meridional winds above Fort Collins, CO (40.6N, 105W), *J. Geophys. Res.,* 2006 [in press].

Tao, Y., C. Y. She, M. E. Hagan, and R. G. Roble, Seasonal variations of semidiurnal tidal-period perturbations in the mesopause region temperature, zonal and meridional winds above Fort Collins, CO (40.6N, 105W), *J. Geophys. Res.,* 2006 [submitted].

Tsuda, T., S. Nozawa, A. Brekke,Y. Ogawa, T. Motoba, R. G. Roble, and R. Fujii, An ion-drag contribution to the lower-thermosphere-wind in summer polar region., *J. Geophys. Res.,* 2006 [in press].

Crowley, G., C. Hackert, R. R. Meier, D. J. Strickland, L. J. Paxton, X. Pi, A. Manucci, A. Christensen, D. Morrison, G. Bust, R. G. Roble, N. Curtis, and G. Wene, Global thermosphere-ionosphere response to onset of November 20, 2003 magnetic storm, *Geophys. Res. Lett.*, 2006 [in press].

Qian, L., S. C. Solomon, R. G. Roble, and T. J. Kane, Model calculation of climate change in the thermosphere, *Geophys. Res. Lett.*, 2006 [in press].

Russell, J. P., W. E. Ward, R. P. Lowe, R. G. Roble, G. G. Shepherd, and B. Solheim, Atomic oxygen profiles (80−115 km) derived from WINDII/UARS measurements of the hydroxyl and greenline airglow: II. Local time-latitude dependence, *J. Geophys. Res.*, 2006 [in press].

Nozawa, S., A. Brekke, S. Maeda, T. Aso, C. Hall, Y. Ogawa, S. C. Buchet, J. Rottger, A. D. Richmond, R. G. Roble, and R. Fujii, Mean winds, tides and quasi-2 day wave in the polar lower thermosphere based on EISCAT eight day run data in November 2003, *J. Geophys. Res.,* 2006 [in press].

Taylor, M. J., A. K. Taori, D. R. Hatch, H.-L. Liu, and R. G. Roble, Characterization of the semi-annual-oscillation in mesospheric temperatures at low-latitudes, *Geophys. Res. Lett.*, 2006 [in press].

Riggin, D. M., H.-L. Liu, R. S. Liberman, R. G. Roble, J. M. Russell III, C. J. Mertens, M. G. Mlynczak, D. Panecheva, S. J. Franke, Y. Murayama, A. H. Manson, and C. E. Meek, Climatology of the 5-day wave, *J. Atmos. Sol.-Terr. Phys*., 2006 [in press].

Birks, J. W., P. J. Crutzen, and R. G. Roble, Frequent ozone depletion resulting from impacts of asteriods and comets, *Comet/Asteroid Impacts and Human Society,* (Peter Bobrowsky and Hans Rickman, Eds.), Springer Verlag, 2005 [in press].

Xu, J., H.-L. Liu, W. Yuan, A. K. Smith, R. G. Roble, C. J. Mertens, J. M. Russell III, and M. G. Mlynczak, Mesopause structure from TIMED/SABER observations, *J. Geophys. Res. (Atmosphere)*, 2006 [submitted].

Matsuo, T., H.-L. Liu, J. L. Anderson, D. Marsh, and A. K. Smith, On model error growth in applications of an ensemble Kalman filter to the mesosphere and lower thermosphere region, *J. Geophys. Res. (Atmosphere)*, 2006 [submitted].

Jackman, C. H., R. G. Roble, and E. L. Flemming, Mesospheric and upper dynamical changes induced by the solar protons events in October-November 2003, *Geophys. Res. Lett.*, 2006 [submitted].

Presentations in FY2006

“On Global Change in the Earth's Upper Atmosphere,” invited paper presented at the “40 Years of Climate Research − A Celebration of Bob Dickinson's Career,” Georgia Tech., Atlanta, GA, October 16−18, 2005.

“Observations of Mesospheric OH and Ozone During the Intense Solar Energetic Particle Event of January 2005,” C. H. Jackman, H. M. Picket, and R. G. Roble, paper presented at the Fall AGU Meeting, San Francisco, CA, December 5−9, 2005.

“Causes of Sub-Auroral Variability of Nitric Oxide in the Thermosphere,” E. R. Talaat, J. Yee, G. Crowley, J. Russell III, M. Mlynczak, R. G. Roble, and S. Bailey, paper presented at the Fall AGU Meeting, San Francisco, CA, December 5−9, 2005.

“The Effect of IMF By on Thermospheric Composition at High and Middle Latitudes,” T. J. Immel, G. Crowley, C. L. Hackert, J. D. Craven, and R. G. Roble, paper presented at the Fall AGU Meeting, San Francisco, CA, December 5−9, 2005.

“Diurnal Nonmigrating Tides from TIDI Wind Measurements: Monthly Climatologies,” J. Oberheide, M. E. Hagan, Q. Wu, T. L. Killeen, and R. G. Roble, paper presented at the Fall AGU Meeting, San Francisco, CA, December 5−9, 2005.

“Effects of Auroral Precipitation on Ionosphere and Thermosphere, G. Lu, A. D. Richmond, R. G. Roble, and T. Immel, paper presented at the Fall AGU Meeting, San Francisco, CA, December 5−9, 2005.

“Diurnal Nonmigrating Tides from TIDI Wind Measurements: Monthly Climatologies,” J. Oberheide, M. E. Hagan, Q. Wu, T. L. Killeen, and R. G. Roble, paper presented at the EGU Meeting, Vienna, Austria, April 2−7, 2006.

“Dynamical Changes Induced by the Solar Proton Events in October−November 2003,” C. Jackman R. G. Roble, and E. Flemming, paper presented at the Spring AGU Meeting, Baltimore, MD, May 23−26, 2006.

“Day-to-Day Variability of the Ionosphere: Comparison of Model Results and Data for a Full Year,” M. Mendillo, R. G. Roble, J. Wroten, and H. Rishbeth, paper presented at the Spring AGU Meeting, Baltimore, MD, May 23−26, 2006.

“Calculation of Thermospheric Neutral Density Secular Change Using a Global Mean Upper Atmosphere Model,” L. Qian, R. G. Roble, S. C. Solomon, and T. J. Kane, paper presented at the Spring AGU Meeting, Baltimore, MD, May 23−26, 2006.

“Solar Influences on the Upper Atmosphere (Mesosphere and Thermosphere),” R. G. Roble, invited paper presented at the Solar Variability (SolVar) Workshop, Boulder, CO, June 13, 2006.

“Study of an Ion-Drag Contribution to the Lower Thermospheric Wind in the Summer Polar Cap Using the RSR Data,” T. Tsuda, S. Nozawa, A. Brekke, Y. Ogawa, T. Motoba, R. G. Roble, and R. Fiji, paper presented at the annual CEDAR Workshop, Santa Fe, NM, June 19−23, 2006.

“Comparison of the Long-Term Incoherent Scatter Radar Ionospheric Temperature Data at Low-Middle Latitudes with the TIEGCM Model,” J. Lei, A. D. Richmond, R.G. Roble, W. Wang, B. Emery, and S.-R. Zhang, paper presented at the COSPAR Meeting, Beijing, China, July 16−23, 2006.

“Thermospheric Neutral Density Response to Solar Forcing,” L. Qian, S. C. Solomon, R. G. Roble, B. R. Bowman, and F. A. Marcos, paper presented at the COSPAR Meeting, Beijing, China, July 16−23, 2006.

“Nonmigrating Tidal Effects in the Earth’s Upper Atmosphere,” M. E. Hagan, A. Maute, R. G. Roble and A. D. Richmond, paper presented at the 3rd IAGA/ICMA Workshop on “Vertical Coupling in the Atmosphere-Ionosphere System,” Varna, Bulgaria, September 20−24, 2006.

“Atmospheric Coupling as Shown in the Stratospheric Sudden Warming,” H.-L. Liu, invited presentation at the Western Pacific Geophysical Meeting, Beijing, China, July 24−27, 2006.

“Chaotic Divergence in a Whole Atmosphere Climate Model,” H.-L. Liu, F. Sassi, R. R. Garcia, and B. A. Boville, paper presented at the 36th COSPAR Scientific Assembly, Beijing, China, July 16−23, 2006.

“Comparative Study of Short Term Tidal Variability,” H.-L. Liu, T. Li, C.-Y. She, J. Oberheide, Q. Wu, M. E. Hagan, J. Xu, and R. G. Roble, paper presented at the Spring AGU Meeting, New Orleans, LA, May 23−27 2005.

“The Mesospheric Surf Zone as Observed by the CRISTA Satellite Instrument and Modeled by the TIME-GCM,” J. Oberheide, H.-L. Liu, G. P. Preusse, D. Offermann, paper presented at the EGU Meeting, Nice, France, 2005.

HONORS/AWARDS/PRIZES

Raymond G. Roble was designated “Highly Cited Researcher” by ISIHighlyCited.com for his influence in the category of Space Sciences as measured by citations to his work. Those cited comprise less than one-half of one percent of all publishing researchers. Further information can be found at http://isihighlycited.com

World Meteorological Organization Norbert-Gerbier Mumm Award for 2005 for the paper “Review of Mesospheric Temperature Trends” published in *Reviews of Geophysics* in 2003. http://www.wmo.ch/news/news.html

UARS Team - NASA Honor Group Achievement Award 2006, Co-I 4 instrument teams on UARS, HRDI, PEM, Solstice, WINDII.